

# Observations of Jovian Electrons at 1 AU

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It has recently been suggested that electrons of Jovian origin are responsible for the 'quiet time increases' in the  $>3$ -MeV electron intensity observed at 1 AU. Using data from the California Institute of Technology electron/isotope spectrometers on Imp 7 and 8, we have studied the temporal behavior of quiet time electrons at 1 AU over the period October 1972 through May 1975. We find the 1- to 6-MeV electron intensity to vary by a factor of  $\sim 10$  from one quiet time period to another, including numerous short-term enhancements characteristic of the quiet time increases reported during 1964–1972. The magnitude and frequency of the increases grow abruptly and remain high for a  $\sim 4$ -month period beginning with the time at which the interplanetary field line first connects earth and Jupiter. It is suggested that the interconnection of the interplanetary field with an extended Jovian magnetotail of  $\sim 2$  AU in length could result in the observed longitudinal distribution of Jovian electrons at 1 AU.

## INTRODUCTION

Extensive studies of  $\sim 3$ - to 12-MeV interplanetary electrons over the past decade have established the complex temporal behavior of this relativistic cosmic ray component [McDonald *et al.*, 1972]. An intriguing aspect of these studies was the identification of a class of intensity variations apparently unique to the low-energy electron component, in which the quiet time electron intensity occasionally increased by a factor of  $\sim 3$ –5 for periods of  $\sim 5$ –14 days. Similar studies have been reported by Webber *et al.* [1973]. Recently, Pioneer 10 observations of interplanetary electron bursts in the vicinity of Jupiter [Chenette *et al.*, 1974; Teegarden *et al.*, 1974] led to the suggestion that electrons of Jovian origin were responsible for the quiet time increases observed at earth [Teegarden *et al.*, 1974]. The apparent 13-month periodicity of the electron increases observed during the years 1964–1972 was consistent with this idea.

In this paper we report observations of the temporal behavior of  $\sim 1$ - to 6-MeV electrons over the period October 1, 1972, to May 13, 1975. These observations support the suggestion that Jovian electrons are responsible for the quiet time increases at 1 AU. An important unresolved aspect of the observation of Jovian electrons is the broad longitudinal extent of the quiet time increases at 1 AU. We suggest that this characteristic and other reported characteristics of quiet time electron increases may result from the interconnection of the interplanetary magnetic field with an extended Jovian magnetotail. A preliminary account of this work has been reported by Mewaldt *et al.* [1975].

## INSTRUMENTATION

The observations reported here were made with the California Institute of Technology electron/isotope spectrometers (EIS) on Imp 7 (launched September 1972) and Imp 8 (launched October 1973). Imp 7 is in an approximately circular orbit of  $\sim 34 R_E$ , while the Imp 8 orbital radius ranges from  $\sim 24$  to  $\sim 45 R_E$ . Both satellites therefore spend a majority of their time in interplanetary space outside the earth's magnetosphere.

Each of the two EIS instruments, which are similar in design and operation, consists of a stack of 11 silicon solid state detectors surrounded by a plastic scintillator anticoincidence cup. A description of the Imp 7 EIS appears in a paper by Hurford *et al.* [1974]. In the EIS, electrons and nuclei are

unambiguously identified by a combination of energy loss, total energy, and range information. The present analysis is restricted to events that trigger at least two 1-mm solid state detectors and then stop within the detector stack. The nominal electron energy interval for such events is  $\sim 1$  to  $\sim 6$  MeV. Data from a separate analysis mode have been used to monitor the flux of  $\sim 0.2$ - to  $\sim 1$ -MeV electrons in order to identify quiet time periods free of significant solar or magnetospheric electron contamination.

As was discussed by Hurford *et al.* [1974], secondary electrons produced by the interaction of  $\gamma$  rays within the detector stack result in a background of electronlike events with an essentially constant rate. This background, which is monitored in a special neutral particle analysis mode of the EIS, has been subtracted from the observed electron rates by using the results of prelaunch calibrations of the EIS  $\gamma$  ray response. Although the  $\gamma$  ray background accounts for  $\sim 70\%$  of the observed electronlike events during the occasional days when the lowest counting rates are observed, this background contribution is essentially constant in time and therefore makes a minor contribution during electron increases.

## OBSERVATIONS

In order to study the quiet time behavior of  $\geq 1$ -MeV electrons it is necessary to identify and exclude periods of significant solar electron activity. The 0.2- to 1-MeV electron count rate is useful for this purpose, since the energy spectra of solar flare electrons [e.g., Simnett, 1974] typically have spectral indices ( $\gamma$ ) of  $\sim 3$  (where  $dJ/dE \propto E^{-\gamma}$ ), while the quiet time spectra that we observe have  $\gamma \simeq 1.3$ –1.7 [Mewaldt *et al.*, 1975]. In addition, highly variable fluxes of low-energy electrons are periodically encountered by Imp 7 and 8 as they traverse the earth's magnetotail every  $\sim 12$  days. These magnetospheric electrons typically have soft spectra with  $\gamma \sim 4$ , and they are therefore readily identified by the 0.2- to 1-MeV electron count rate. Note that the periods during which Imp 7 and 8 were within the magnetotail do not in general coincide, because the two satellites were  $\sim 90^\circ$  to  $\sim 270^\circ$  out of phase during this study.

Figure 1 shows a plot of the daily average quiet time count rates of 1- to 6-MeV electrons for days during which the flux of 0.2- to 1-MeV electrons was  $\leq 0.2 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ . This criterion includes the observed range of quiet time intensity variations but eliminates both those periods of significant solar electron enhancement and those days when significant fluxes of magnetospheric electrons were observed. The total number of days

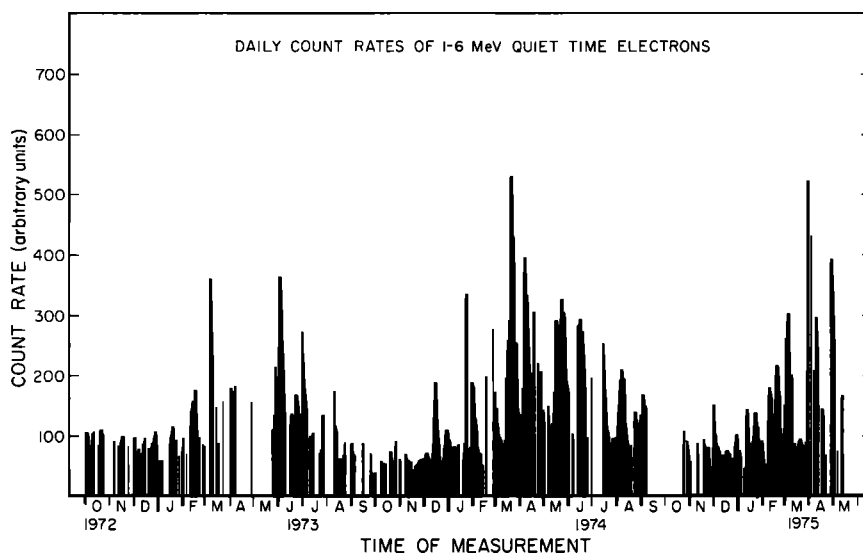


Fig. 1. Daily count rates of 1- to 6-MeV electrons (October 1972 to May 1975). Days with significant solar or magnetospheric electron contamination have been excluded. Count rates from November 1, 1973, to April 14, 1975, are based on both Imp 7 and Imp 8 data. Statistical uncertainties are typically  $\lesssim 5\%$ .

satisfying this quiet time criterion was found to be relatively insensitive to the exact value of the 0.2- to 1-MeV flux limit. In Figure 1, daily count rates from November 1, 1973, to April 14, 1975, are based on suitably normalized data from both satellites in order to provide more complete coverage outside the earth's magnetosphere.

Notice in Figure 1 that the 1- to 6-MeV electron intensity during late 1972, 1973, and 1974 was relatively stable. However, the count rates in early 1973, 1974, and 1975 are dominated by a number of large intensity increases with typical duration of  $\sim 10$  days, during which the 1- to 6-MeV electron intensity increases by up to a factor of  $\sim 10$ . Similar behavior is observed in the  $\sim 3$ - to 6-MeV interval. Inspection of our low-energy ( $\sim 1$  MeV) proton counting rates shows that the increases are generally anticorrelated with solar proton activity. In addition, the increases often exhibit an apparent periodicity consistent with the 27-day solar rotation period. The above behavior is consistent with that found in the quiet time increases identified by McDonald *et al.* [1972] and Teegarden *et al.* [1974] during 1964–1972.

In order to study the frequency of occurrence of quiet time electron increases it is useful to consider longer-term averages of the electron intensity. Figure 2 shows monthly average count rates of 1- to 6-MeV and 3- to 6-MeV electrons for the days shown in Figure 1. Notice that the average monthly count rates show relative maxima in early 1973 and 1974 that are  $\sim 3$  times the minimum monthly rates. Comparison of the 1- to 6-MeV and 3- to 6-MeV rates shows that they track each other well, a result indicating that the average slope of the quiet time electron energy spectrum did not vary significantly from month to month. Figure 2 also indicates the nominal time of interplanetary magnetic field line connection between earth and Jupiter, when a solar wind velocity of 400 km/s is assumed. The monthly average electron rates show a behavior consistent with the predicted 13-month periodicity expected from Jovian electrons, although the rates remain high for several months beyond the time of nominal connection, as was also noted by Teegarden *et al.* [1974].

## DISCUSSION

The results of this study of quiet time interplanetary electrons for the period October 1972 to May 1975 are in general consistent with reported observations at somewhat higher energy during previous years. We find that over a significant portion of this 2½-year period the quiet time electron intensity was dominated by quiet time increases.

An important unresolved aspect of the observation of Jovian electrons at 1 AU is the large longitudinal extent of the quiet time increases. As is shown in Figures 1 and 2, the increases abruptly grow at the approximate time when the nominal interplanetary field line connects Jupiter and earth. However, the amplitudes of the increases then remain high for  $\sim 4$  months, which corresponds to  $\sim 110^\circ$  in solar longitude. As was pointed out by Teegarden *et al.* [1974], to explain this effect as the corotation of an interplanetary flux tube that was loaded with electrons as it passed Jupiter would require a much longer electron containment time ( $\sim 8$  days) than is observed during solar electron events, which have decay times of  $\lesssim 1$  day [e.g., Simnett, 1974].

An alternative possibility, shown schematically in Figure 3,

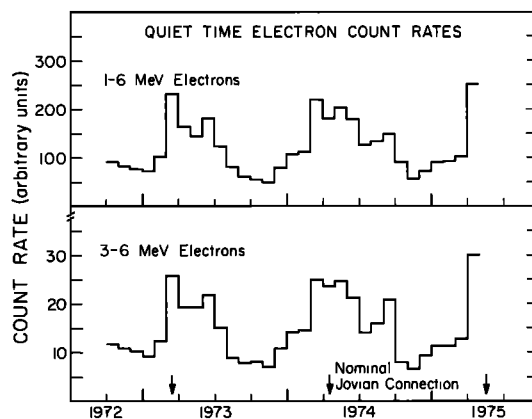


Fig. 2. Monthly average count rates of quiet time electrons (Imp 7 data only).

is to have continuing injection of Jovian electrons on the field lines for a period of  $\sim 8$  days after they have passed Jupiter. If the interplanetary and Jovian magnetic fields were interconnected because of magnetic merging and if the Jovian magnetotail were  $\sim 2$  AU in length, then such continuing injection might occur naturally.

Although the large-scale configuration of the Jovian magnetosphere is not understood, it is possible to estimate the length of a possible magnetotail if it is assumed, for example, that the polar Jovian magnetic field is merged with the interplanetary field, as is thought to be the case for earth (see, e.g., the review by Paulikas [1974]). The total interplanetary flux merged at any moment can be roughly estimated to be  $\sim 2B_{ip}R_mL$ , where  $B_{ip}$  is the interplanetary field intensity,  $2R_m$  is the width of the magnetotail, and  $L$  is the length. The corresponding merged polar flux is  $\sim B_pA_p$ , where  $B_p$  is the polar surface field intensity and  $A_p$  is the polar area of the open field lines. Since the two merged fluxes must be equal, we find  $L \sim B_pA_p/2B_{ip}R_m$ . Assuming that the polar region above  $\sim 65^\circ$  is open [e.g., Hill *et al.*, 1974; Goertz *et al.*, 1974], as is the case for earth, and that  $B_p \sim 8$  G,  $B_{ip} \sim 5 \times 10^{-6}$  G, and  $R_m \sim 100 R_J$ , where  $R_J$  is the radius of Jupiter, we find that  $L \sim 3.4 \times 10^8$  km  $\sim 2$  AU. It thus seems plausible that the duration of electron enhancements at earth may be the result of an extended Jovian magnetotail and that it may be unnecessary to consider extended containment times or cross-field diffusion processes.

Other reported characteristics of quiet time increases may also be explained by this picture. For example, the confinement of the electron increases within individual interplanetary magnetic field sectors [McDonald *et al.*, 1972] might result from the discontinuous merging pattern to be expected at the interface of a sector boundary with the Jovian magnetotail.

Also shown in Figure 3 is the Pioneer 10 trajectory before and after its December 3, 1973, Jovian encounter. Pioneer 10 observed bursts of Jovian electrons as far as  $\sim 1$  AU away from the planet during the  $\sim 6$  months prior to encounter [Teegarden *et al.*, 1974; Chenette *et al.*, 1974]. Note that during this preencounter period, Pioneer 10 and Jupiter were not directly connected by the nominal interplanetary magnetic field direction indicated in Figure 3. However, examples of these preencounter electron events studied by Smith *et al.* [1976] were found to occur at times when the interplanetary magnetic field direction at Pioneer 10 was distorted to the extent that it apparently did intercept the Jovian magnetosphere, a result indicating that the electron bursts were propagating primarily along the interplanetary field rather than across it.

Large-scale field line distortion due to solar wind velocities greater than 400 km/s could presumably result in an earth-Jupiter connection at times earlier than those indicated in Figure 2, providing a natural explanation for apparently premature electron increases such as the increase in mid-December 1973 (see Figure 1). It appears unlikely, however, that solar wind velocity variations alone could account for electron increases which occur 4 months after the time of nominal connection (see Figure 2), since this would require that the average solar wind velocity be  $\sim 270$  km/s for an entire solar rotation.

If the interplanetary magnetic field does in fact merge with the Jovian magnetosphere to the extent indicated in Figure 3, we would expect Pioneer 10 to have observed Jovian electrons for up to  $\sim 1$  year following the December 1973 Jovian encounter or until Pioneer 10 was at sufficiently higher heliogra-

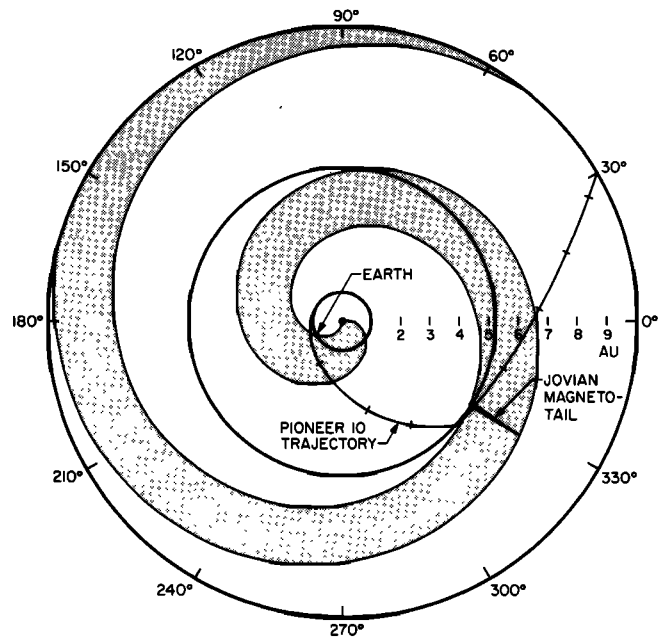


Fig. 3. A heliocentric plot showing the shaded region in which the interplanetary magnetic field might be interconnected with an extended Jovian magnetotail of  $\sim 2$  AU in length. A solar wind velocity of 400 km/s has been assumed. Earth and Jupiter positions are for April 1974. The tick marks on the Pioneer 10 trajectory mark 6-month intervals from Jovian encounter on December 4, 1973.

phic latitude than Jupiter. This time period includes the large quiet time increases observed at earth in early 1974 (see Figure 1). Although postencounter Pioneer 10 electron observations have not as yet been reported, simultaneous observations of Jovian electrons at 1 and  $>5$  AU would provide an attractive means of studying particle propagation in the interplanetary medium. Furthermore, the quiet time electron enhancements could provide an important tool in studying the large-scale Jovian magnetosphere.

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## REFERENCES

- Chenette, D. L., T. F. Conlon, and J. A. Simpson, Bursts of relativistic electrons from Jupiter observed in interplanetary space with the time variation of the planetary rotation period, *J. Geophys. Res.*, **79**, 3551, 1974.
- Goertz, C. K., B. A. Randall, and M. F. Thomsen, A model for the Jovian magnetic field (abstract), *Eos Trans. AGU*, **55**, 1172, 1974.
- Hill, T. W., A. J. Dessler, and F. C. Michel, Configuration of the Jovian magnetosphere, *Geophys. Res. Lett.*, **1**, 3, 1974.
- Hurford, G. J., R. A. Mewaldt, E. C. Stone, and R. E. Vogt, The energy spectrum of 0.16 to 2 MeV electrons during solar quiet times, *Astrophys. J.*, **192**, 541, 1974.
- McDonald, F. B., T. L. Cline, and G. M. Simnett, Multifarious temporal variations of low-energy relativistic cosmic ray electrons, *J. Geophys. Res.*, **77**, 2213, 1972.
- Mewaldt, R. A., E. C. Stone, and R. E. Vogt, Observations of low energy interplanetary electrons, *Proc. Int. Conf. Cosmic Rays 14th*, **2**, 758, 1975.
- Paulikas, G. A., Tracing of high-latitude magnetic field lines by solar particles, *Rev. Geophys. Space Phys.*, **12**, 117, 1974.
- Simnett, G. M., Relativistic electron events in interplanetary space, *Space Sci. Rev.*, **16**, 257, 1974.

- Smith, E. J., B. T. Tsurutani, D. L. Chenette, T. F. Conlon, and J. A. Simpson, Jovian electron bursts: Correlation with the interplanetary magnetic field direction and hydromagnetic waves, *J. Geophys. Res.*, **81**, 65, 1976.
- Teegarden, B. J., F. B. McDonald, J. H. Trainor, W. R. Webber, and E. C. Roelof, Interplanetary MeV electrons of Jovian origin, *J. Geophys. Res.*, **79**, 3615, 1974.
- Webber, W. R., J. A. Lezniak, and S. V. Damle, Cosmic ray electrons from 0.2 to 8 MeV: Pioneer 8 and 9 measurements of their spectrum, time variations, and interplanetary radial gradient, *J. Geophys. Res.*, **78**, 1487, 1973.

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